CORPORATION ROBOTS

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A thesis submitted in fulfillment of the requirement for the award of the

Degree of Master of Electrical Engineering

Faculty of Electrical and Electronic Engineering

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November 2011

ABSTRACT

In this thesis, a simulation package for the Six Degrees of Freedom (6DOF) motion of an underwater vehicle is developed. Mathematical modeling of an underwater vehicle is done and the parameters needed to write such a simulation package are obtained from an existing underwater vehicle available in the literature.

Basic equations of motion are developed to simulate the motion of the underwater vehicle and the parameters needed for the hydrodynamic modeling of the vehicle is obtained from the available literature.

6DOF simulation package prepared for the underwater vehicle was developed using the MATLAB environment. S-function hierarchy is developed using the same platform with C++ programming language. With the usage of S-functions the problems related to the speed of the platform have been eliminated. The use of S- function hierarchy brought out the opportunity of running the simulation package on other independent platforms and get results for the simulation.
Keywords: Underwater Vehicle Simulation, Virtual Reality Modeling Language (VRML), MATLAB S-function, Simulink, C++, 6DOF.

ABSTRAK

Di dalam tesis in , satu pakej simulasi untuk pergerakan Enam Darjah Kebebasan (6 DOF) untuk kenderaan di dalam air telah dibangunkan. Permodelan matematik untuk kenderaan di dalam air telah diterbitkan dan paramter-parameter yang diperlukan untuk dimasukan dalam pakej simulasi telah diperolehi daripada kajian literatur.

Persamaan asas gerakan untuk mensimulasikan pergerakan kenderaan di dalam air telah dibangunkan dan parameter-parameter yang diperlukan bagi pemodelan hidrodinamik kenderaan ini telah perolehi daripada kajian literatur yang sedia ada.

Pakej simulasi 6DOF yang disediakan untuk kenderaan di dalam air telah dibangunkan dengan menggunakan perisian MATLAB. Hierarki fungsi-S telah dibangunkan dengan platform yang sama dengan menggunakan pengaturcaraan bahasa C++. Dengan penggunaan fungsi-S masalah-masalah yang berkaitan dengan kelajuan platform yang telah diselesaikan. Penggunaan hierarki fungsi-S yang memberi peluang untuk menjalankan pakej simulasi di platform yang lain untuk mendapat keputusan untuk simulasi tersebut.

Keywords: Simulasi Kenderaan di dalam air, Virtual Reality Modeling Language (VRML), MATLAB fungsi -S, Simulink, C + +, 6DOF.

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LIST OF SYMBOLS

x, y, z	Axes of body fixed reference frame
X, Y, Z	Axes of earth fixed reference frame
x	Linear velocity along the North-South axis (earth)
y	Linear velocity along the East- West axis (earth)
z	Linear velocity along the vertical axis (earth)
ϕ	Euler angle in North-South axis. Positive sense is clockwise as seen from back of the vehicle (earth)
θ	Euler angle in pitch plane. Positive sense is clockwise as seen from port of the vehicle (earth)
ψ	Euler angle in yaw plane. Positive sense is clockwise as seen from above (earth)
ϕ	Roll Euler rate about North-South axis (earth)
θ	Pitch Euler rate about East-West axis (earth)
ψ	Roll Euler rate about North-South axis (earth)
u	Linear velocity along longitudinal axis (body)
v	Linear velocity along horizontal plane (body)
w	Linear velocity along depth (body)
p	Angular velocity component about body longitudinal axis
q	Angular velocity component about body lateral axis
r	Angular velocity component about body vertical axis
u	Time rate of change of velocity along the body longitudinal axis
v	Time rate of change of velocity along the body lateral

	axis
w	Time rate of change of velocity along the body vertical axis
p	Time rate of change of body roll angular velocity about the body longitudinal axis
q	Time rate of change of body pitch angular velocity about the body lateral axis
r	Time rate of change of body yaw angular velocity about the body vertical axis
δ_r	Stern rudder deflection angle. (It is noted as Stern, since the vehicle used in this thesis has both bow and stern rudders. But just stern rudders are used throughout the simulation.
δ_e	Stern planes (elevator) deflection angle. (It is noted as Stern plane, since the vehicle used in this thesis has both bow and stern planes. But just stern planes are used throughout the simulation.
n	Propeller revolutions per minute
W	Weight of the vehicle
B	Buoyancy of the vehicle
L	Length of the vehicle. *Also known as characteristic length. Dynamic equations of motion are written to explicitly utilize L as normalization coefficient.* [6]
g	Acceleration due to gravity
ρ	Density of fluid
D_2	$0.5 \ \rho L^2$
D_3	$0.5 \ \rho L^3$
D_4	$0.5 \rho L^4$

D_5	$0.5\ \rho L^5$
W	Weight
m	mass
B	Buoyancy
I_{xx}	Mass Moment of Inertia about x-axis
I_{yy}	Mass Moment of Inertia about y-axis
I_{zz}	Mass Moment of Inertia about z-axis
I_{xy}	Cross Product of Inertia about xy-axes
I_{yz}	Cross Product of Inertia about yz-axes
I_{xz}	Cross Product of Inertia about xz-axes
CG	Center of gravity
x_G	x Coordinate of CG From Body Fixed Origin
y_G	y Coordinate of CG From Body Fixed Origin
z_G	z Coordinate of CG From Body Fixed Origin
CB	Center of buoyancy
x_B	x Coordinate of CB From Body Fixed Origin
y_B	y Coordinate of CB From Body Fixed Origin
z_B	z Coordinate of CB From Body Fixed Origin
C_{d0}	Drag coefficient along longitudinal axis (body)
$K_1, k_1, K_2, k_2, kcd,$ $k_q, k_\Theta, k_{d\Theta}, C1, C2$	Controller gains
H, G	Plants simulating the dynamic model
X_u	Drag contribution in the longitudinal X direction due to time rate of change of u [6]
X_{pp}	Drag force due to square of roll rate of body
X_{qq}	Drag force due to square of pitch rate of body

X_{rr}	Drag force due to square of yaw rate of body
X_{pr}	Drag force due to r and p
X_{wq}	Drag force due to q and w
X_{vp}	Drag force due to p and v
X_{vv}	Drag force due to square of v
X_{ww}	Drag force due to square of w
η	Steady state speed per maximum propeller revolutions per minute (rpm)
$X_{\delta_r \delta_r}$	Drag force due to square deflection angle of rudder respectively due to square of u
$X_{\delta_e \delta_e}$	Drag force due to square deflection angle of elevator respectively due to square of u
$X_{w\delta_e}$	Drag force due to deflection angle of elevator respectively due to w
$X_{v\delta_r}$	Drag force due to deflection angle of rudder and v
$X_{q\delta_e}$	Drag force due to deflection angle of elevator and q
$X_{r\delta_r}$	Drag force due to deflection angle of rudder and r.
Y_p	Sway force due to time rate of change of p
Y_r	Sway force due to time rate of change of r
Y_{pq}	Sway force due to q and p
Y_{qr}	Sway force due to r and q
Y_v	Sway force due to time rate of change of v
Y_{up}	Sway force due to p and u

Y_{ur}	Sway force due to r and u
Y_{vq}	Sway force due to q and v
$Y_{\omega p}$	Sway force due to p and w
Y_{wr}	Sway force due to r and w
Y_{vq}	Sway force due to q and v
Y_{wp}	Sway force due to p and w
Y_{wr}	Sway force due to r and w
Z_{q}	Heave force due to time rate of change of q
Z_{pp}	Heave force due square of p
Z_{pr}	Heave force due to r and p
Z_{rr}	Heave force due to square of r
Z_{w}	Heave force due to time rate of change of w
Z_{q}	Heave force due to q
Z_{vp}	Heave force due to p and v
Z_{vr}	Heave force due to r and v
Z_{w}	Heave force due to w
Z_{vv}	Heave force due to square of v
Z_{δ_e}	Heave force due to elevator deflection
K_{p}	Roll moment due to time rate of change of p
K_{r}	Roll moment due to time rate of change of r
K_{pq}	Roll moment due to q and p
K_{qr}	Roll moment due to r and q

K_v	Roll moment due to time rate of change of v
K_p	Roll moment due to time rate of change of p
K_r	Roll moment due to r
K_{vq}	Roll moment due to q and v
K_{wp}	Roll moment due to p and w
K_{wr}	Roll moment due to r and w
K_v	Roll moment due to v
K_{vw}	Roll moment due to w and v
M_q	Pitch moment due to time rate of change of q
M_{pp}	Pitch moment due to square of p
M_{pr}	Pitch moment due to r and p
M_{rr}	Pitch moment due to square of r
M_w	Pitch moment due to time rate of change of w
M_{uq}	Pitch moment due to q and u
M_{vp}	Pitch moment due to p and v
M_{vr}	Pitch moment due to r and v
M_w	Pitch moment due to w
M_{vv}	Pitch moment due to square of v
M_{δ_e}	Pitch moment due elevator deflection
N_p	Yaw Moment due to time rate of change of p
N_r	Yaw Moment due to time rate of change of r
N_{pq}	Yaw Moment due to q and p

N_{qr}	Yaw Moment due to r and q
N_{v}	Yaw Moment due to time rate of change of v
N_{p}	Yaw Moment due to p
N_{r}	Yaw Moment due to r
N_{vq}	Yaw Moment due to q and v
N_{wp}	Yaw Moment due to p and w
N_{wr}	Yaw Moment due to r and w
N_{v}	Yaw Moment due to v
N_{vw}	Yaw Moment due to w

CHAPTER 1

INTRODUCTION

1.1 Simulation of Motion of an Underwater Vehicle

One of the safest ways to explore the underwater is using small unmanned vehicles to carry out various missions and measurements, among others, can be done without risking people's life. With the advent of underwater vehicles, the researchers capability to investigate the deep waters is extremely improved. Today underwater vehicles are becoming more popular especially for environmental monitoring and for defense purposes.

The grooving importance of Autonomous Underwater Vehicles (AUVs) in research areas can easily be understood if the Unmanned Underwater Vehicles (UUV) program for the US Navy described below, is investigated [1]:

"UUV programs will extend knowledge and control of the undersea battle space through the employment of cost-effective, covert, off-board sensors capable of operating reliably in areas of high risk and political sensitivity. They will provide unmanned systems capable of improving, supplementing, or replacing manned systems in order to enhance force efficiency, reduce costs, and reduce risk to people and platforms."

Unmanned Underwater Vehicles (UUVs) fall between the "Remotely Operated Vehicles (ROVs)" and the torpedo. They are being widely used in commercial, scientific and military missions for explorations of water basin, temperature, and composition of the surrounding fluid, current speed, tidal waters and life forms in its natural habitats.

As a result there is a need to investigate the lakes and the coastal waters because of the influences of all changes therein have on people. A platoon of unmanned vehicles could be used to explore the under water environments more thoroughly and efficiently.

This simulation develops and describes software architecture for an underwater vehicle. Interaction with human is realized by means of a joystick input to control the depth and azimuth of the vehicle in 3D. 3D visualization is developed using VRML.

1.2 Literature Survey

There are numerous research communities working on the design and construction of underwater vehicles for different purposes as mentioned in the pervious section. Key papers in this field are primarily found in the proceedings of annual conferences which goes back to 1990s. These include the following conferences:

- IEEE Oceanic Engineering Society (OES) Autonomous Underwater Vehicle (AUV) symposia and OCEANS conferences [2].
- AUV Laboratories MIT, There are several types of underwater vehicles built by different companies. Some specifications of vehicles are presented [3].
- Autonomous Undersea Systems Institute (AUSI): AUSI has been mainly funded through grants from the Office of Naval Research and the National Science Foundation. AUSI also provides its facilities and expertise to support research programs at other institutions and AUSI continues to organize and conduct International Symposia on Unmanned Untethered Submersible Technology. Many kinds of AUVs can be found through the AUSI research center [4].

Also many papers and publications about the Autonomous Underwater Vehicles (AUV) can be found from Center for Autonomous Underwater Vehicle Research of Naval Postgraduate School [5].

Some of representative and pertinent AUV projects are summarized below.

1.2.1 ARPA / Navy Unmanned Undersea Vehicle (UUV)

Laboratories were contracted to build two large UUVs for tactical naval missions, particularly open-ocean minefield search.

Figure 1: ARPA picture captured from [6].

These vehicles are the largest, the most capable and the most expensive AUVs (approximately $9 million) built to date. The ARPA UUVs use high-density silver zinc batteries for 24 hours of operational endurance at 5-10 knots (2.57 – 5.14 m/s) submerged. Weighing 15,000 pounds (680 kg) in air, the vehicles have titanium hulls which permit a test depth of 1,000 feet (305 m)

1.2.2 MIT- Marie Polsenberg Manually Controlled AUV

Manually controlled AUVs can be found throughout literature [7]. For example Ann Marie Polsenberg, MIT can be investigated for this purpose. In this example a lap box is designed to control rudder and elevator of the vehicle displaying the rudder and the elevator deflections on the LCD [7].

Figure 2: A manual control example of an AUV [7]

1.2.3 GAVIA Great Northern Diver

The small size and the deep-water research AUV GAVIA has modular parts developed by Hafmynd Corporation Iceland [8].

Figure 3: GAVIA modular AUV parts [8]

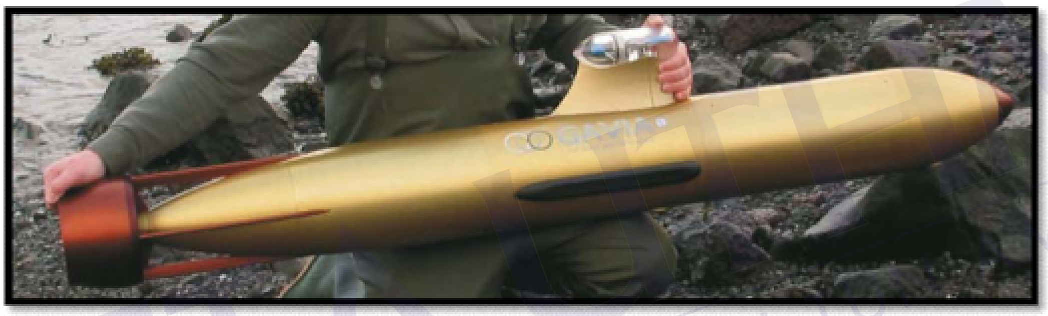

Figure 4: GAVIA AUV [9]

1.2.4 Electric Glider

Gliders are unique in the AUV world, in that the forward propulsion is created by varying vehicle buoyancy [9]. Wings and control surfaces convert the vertical velocity into forward velocity so that the vehicle glides downward when denser than water and glides upward when buoyant (Figure 5). Gliders require no propeller and operate in a vertical saw tooth trajectory.

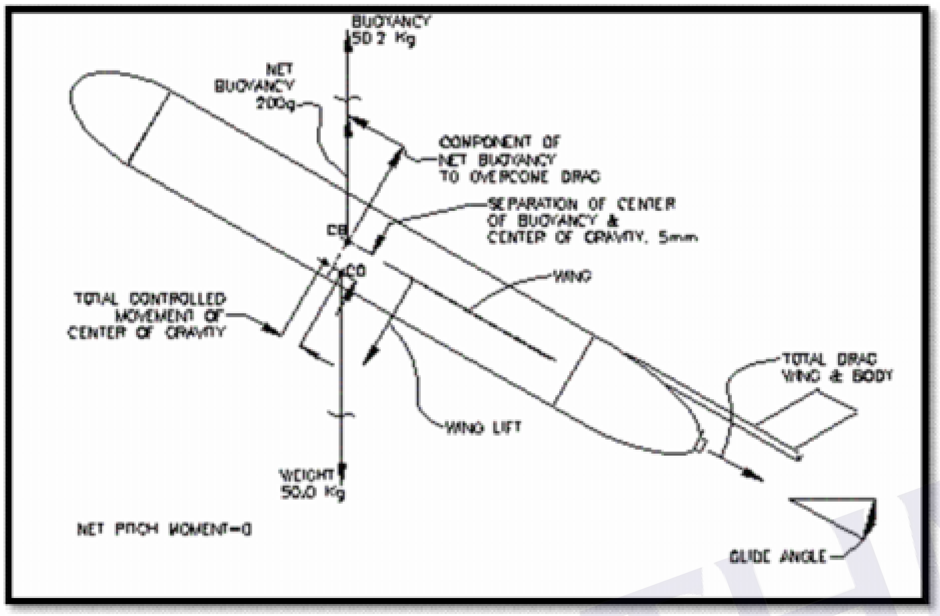

Figure 5: Force balance diagram of forces acting on Glider, angle of attack not included [9]

Figure 6: A picture of Electric Glider. The glider at the back and swept back wings are the main interesting features [9]

1.2.5 REMUS

There are over 70 REMUS (Remote Environmental Measuring Units) autonomous underwater vehicle systems designed for operation in coastal environments from 100 to 6000 meters in depth [10]. These AUVs are designed by Woods Hole Oceanographic Institute (WHOI) and moved out of the institute and into HYDROID Corporation. A picture of the REMUS 600 (Operating up to 600 meters in depth) is given in Figure 7.

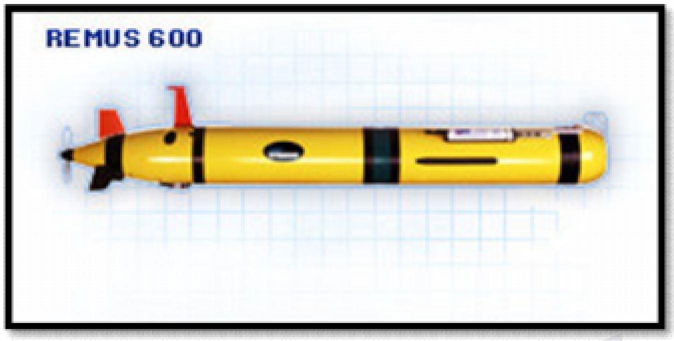

Figure 7: REMUS 600 [10]

1.2.6 Theseus AUV

Another interesting AUV Theseus (Figure 8) was developed by the U.S. and Canadian Defense Establishments to lay long lengths of fiber-optic cable under the Arctic ice pack. The vehicle completed successful deployments to the Arctic in 1995 and 1996. During the 1996 deployment, a 190 km cable was laid at 500 meter depths under a 2.5 meter thick ice pack. The overall mission distance was 365 km, making this the longest AUV mission to date. Its length is 10.7 meters, diameter: 1.27 meters, displacement: 8600 kg (with 220 km cable), nominal Speed: 4 knots [11].

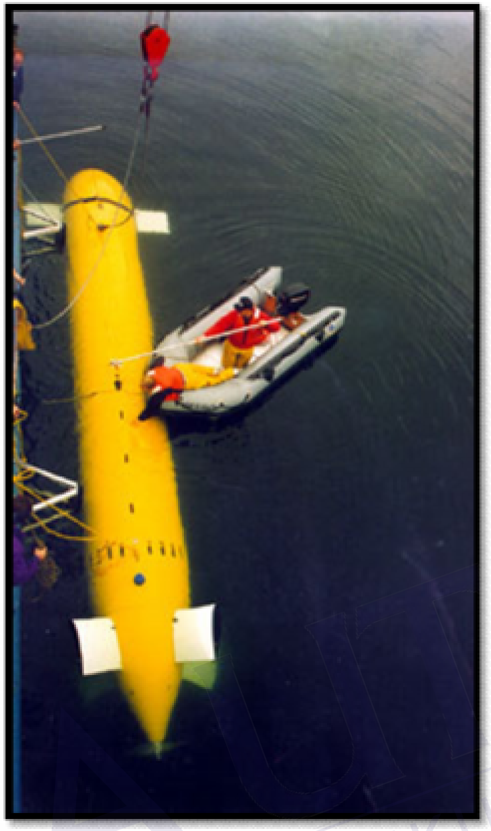

Figure 8: Theseus AUV [11]

1.3 Scope of the Thesis

For modeling of underwater vehicle dynamics, the vehicle designed and operated by the Naval Post Graduate School, NPS AUV II, is used. This vehicle is used as a workbench to support the physics-based AUV modeling and for visualization of the vehicle behavior, animation based on the vehicle-specific hydrodynamics is used. All of the work done in this study can easily be configured to model arbitrary vehicle

1.3.1 Vehicle Profile

In this thesis NPS AUV II is used as the underwater vehicle to be simulated. The schematic drawing of NPS AUV II is shown in Figure 9. The vehicle dimensions and major hydrodynamic components are described below.

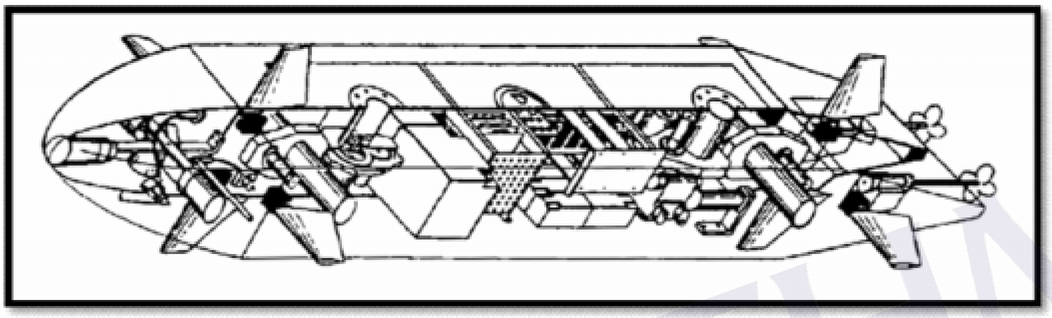

Figure 9: Schematic drawing of NPS AUV II [6].

1.3.1.1 Main Dimensions and Properties

The NPS AUV II has four paired plane surfaces and bidirectional twin propellers. The vehicle is ballasted to be neutrally buoyant at 53400 N. It is slender formed and is 5.3m long. An external view of the vehicle is shown in Figure 10

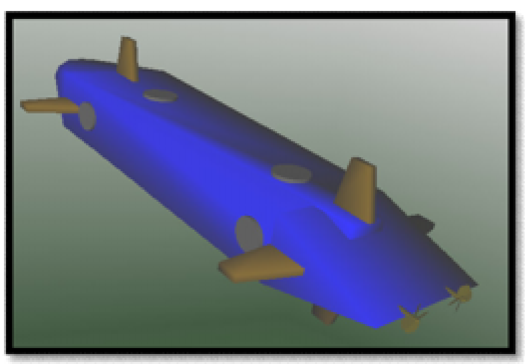

Figure 10: Exterior view of NPS AUV II

The main inertial and hydrodynamic parameters of the NPS AUV II are given in Table 1 to Table 7. All of the hydrodynamic data given in these tables are taken from [12].

Table 1 Physical properties of the underwater vehicle used in the simulation

Parameter	**Description**	**Value**
ρ	Density of fluid	1000 kg / m^3
W	Weight	53400 N
m	Mass	5443.4 kg
B	Buoyancy	53400 N
L	Characteristic Length	5.3 m
I_{xx}	Mass Moment of Inertia about *x*-axis	2038 Nms^2
I_{yy}	Mass Moment of Inertia about *y*-axis	13587 Nms^2
I_{zz}	Mass Moment of Inertia about *z*-axis	13587 Nms^2
I_{xy}	Cross Product of Inertia about *xy*-axes	-13.58 Nms^2
I_{yz}	Cross Product of Inertia about *yz*-axes	-13.58 Nms^2
I_{xz}	Cross Product of Inertia about *xz*-axes	-13.58 Nms^2
x_G	x Coordinate of CG From Body Fixed Origin	0.0 m
y_G	y Coordinate of CG From Body Fixed Origin	0.0 m
z_G	z Coordinate of CG From Body Fixed Origin	0.061 m
x_B	x Coordinate of CB From Body Fixed Origin	0.0 m
y_B	y Coordinate of CB From Body Fixed Origin	0.0 m
z_B	z Coordinate of CB From Body Fixed Origin	0.0 m

Table 2 Surge (Longitudinal) Non – Dimensional Hydrodynamic Coefficients

$X_{u} = -7.6 * 10^{-2}$	$X_{pr} = 7.5 * 10^{-4}$	$X_{ww} = 1.7 * 10^{-1}$	$X_{\delta_e\delta_e} = 1.7 * 10^{-1}$
$X_{pp} = -7.0 * 10^{-3}$	$X_{wq} = -2.0 * 10^{-1}$	$X_{r\delta_r} = -1.0 * 10^{-3}$	$X_{w\delta_e} = 4.6 * 10^{-2}$
$X_{qq} = -1.5 * 10^{-2}$	$X_{vp} = -3.0 * 10^{-3}$	$X_{\delta_r\delta_r} = -1.0 * 10^{-2}$	$X_{v\delta_r} = 1.7 * 10^{-3}$
$X_{rr} = 4.0 * 10^{-3}$	$X_{vv} = 5.3 * 10^{-2}$	$X_{q\delta_e} - 2.5 * 10^{-2}$	

Table 3 Sway (Lateral) Non – Dimensional Hydrodynamic Coefficients

$Y_{p} = 1.2 \times 10^{-4}$	$Y_{v} = -5.5 \times 10^{-2}$	$Y_{\omega p} = 2.3\times 10^{-1}$	$Y_{uv} = -1.9 \times 10^{-2}$
$Y_{r} = 1.2 \times 10^{-3}$	$Y_{up} = 3.0 \times 10^{-3}$	$Y_{wr} = -1.9 \times 10^{-3}$	$Y_{vw} = 6.8 \times 10^{-2}$
$Y_{pq} = 4.0 \times 10^{-3}$	$Y_{ur} = 3.0 \times 10^{-2}$	$Y_{vq} = 2.4 \times 10^{-2}$	$Y_{uv} = -1.0 \times 10^{-1}$
$Y_{qr} = -6.5 \times 10^{-3}$	$Y_{vq} = 2.4 \times 10^{-2}$	$Y_{wp} = 2.3 \times 10^{-1}$	$Y_{\delta_r} = 2.7 \times 10^{-2}$

Table 4 Heave (Vertical) Non – Dimensional Hydrodynamic Coefficients

$Z_{q} = -6.8 \times 10^{-3}$	$Z_{w} = -2.4 \times 10^{-1}$	$Z_{w} = -3.0 \times 10^{-1}$
$Z_{pp} = 1.3 \times 10^{-4}$	$Z_{q} = -1.4 \times 10^{-1}$	$Z_{vv} = -6.8 \times 10^{-2}$
$Z_{pr} = 6.7 \times 10^{-3}$	$Z_{\upsilon p} = -4.8 \times 10^{-2}$	$Z_{\delta_e} = -7.3 \times 10^{-2}$
$Z_{rr} = -7.4 \times 10^{-3}$	$Z_{\upsilon r} = 4.5 \times 10^{-2}$	

Table 5 Roll Non – Dimensional Hydrodynamic Coefficients

$K_p = -1.0 \times 10^{-3}$	$K_\upsilon = 1.2 \times 10^{-4}$	$K_{wp} = -1.3 \times 10^{-4}$
$K_r = -3.4 \times 10^{-5}$	$K_p = -1.1 \times 10^{-2}$	$K_{wr} = 1.4 \times 10^{-2}$
$K_{pq} = -6.9 \times 10^{-5}$	$K_r = -8.4 \times 10^{-4}$	$K_v = 3.1 \times 10^{-3}$
$K_{qr} = 1.7 \times 10^{-2}$	$K_{\upsilon q} = -5.1 \times 10^{-3}$	$K_{vw} = -1.9 \times 10^{-1}$

Table 6 Pitch Non – Dimensional Hydrodynamic Coefficients

$M_q = -1.7 \times 10^{-2}$	$M_w = -6.8 \times 10^{-3}$	$M_{uw} = 1.0 \times 10^{-1}$
$M_{pp} = 5.3 \times 10^{-5}$	$M_{uq} = -6.8 \times 10^{-3}$	$M_{vv} = -2.6 \times 10^{-2}$
$M_{pr} = 5.0 \times 10^{-3}$	$M_{\upsilon p} = 1.2 \times 10^{-3}$	$M_{\delta_e} = -4.1 \times 10^{-2}$
$M_{rr} = 2.9 \times 10^{-3}$	$M_{\upsilon r} = 1.7 \times 10^{-2}$	

Table 7 Yaw Non – Dimensional Hydrodynamic Coefficients

$N_p = -3.4 \times 10^{-5}$	$N_\upsilon = 1.2 \times 10^{-3}$	$N_{wp} = -1.7 \times 10^{-2}$	$N_{\delta_r} = -1.3 \times 10^{-2}$
$N_r = -3.4 \times 10^{-3}$	$N_p = -8.4 \times 10^{-4}$	$N_{wr} = 7.4 \times 10^{-3}$	
$N_{pq} = -2.1 \times 10^{-2}$	$N_r = -1.6 \times 10^{-2}$	$N_v = -7.4 \times 10^{-3}$	
$N_{qr} = 2.7 \times 10^{-3}$	$N_{\upsilon q} = -1.0 \times 10^{-2}$	$N_{vw} = -2.7 \times 10^{-2}$	

1.4 Organization of the Thesis

The purpose of the thesis is to put an effort on the simulation of underwater vehicles. Figure 11 represents the general simulation architecture for the underwater vehicle. Using this figure as a roadmap, the chapters of the thesis is arranged.

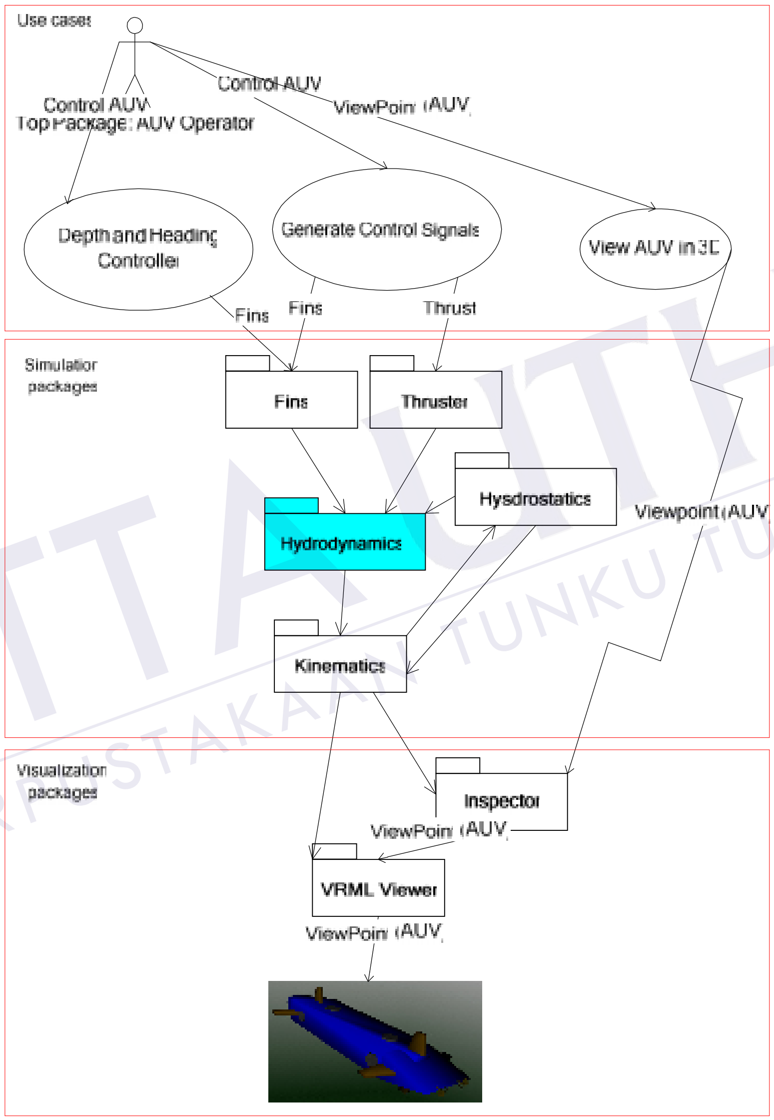

Figure 11: An underwater vehicle simulation architecture

In Chapter II, complete set of nonlinear equations of motion for an underwater vehicle are derived. Kinematics, Newton's laws of angular and linear momentum, hydrodynamics and external force modeling are discussed in detail. Hydrodynamic and thruster models are described including the implementation issues to the simulation model interacting with the manual control inputs.

Chapter III explains the development of control system design for underwater vehicle. In manual control mode of the vehicle, the vehicle can not perform the task of following a desired path adequately. Hence some feedback controllers are needed. This chapter describes the design and analysis of this feedback control system. Two main controllers, for lateral and depth control are developed. In their inner loops, these controllers include the yaw angle and the pitch attitude controllers. Yaw angle and the pitch attitude controllers are separated from the main controllers in order to keep the vehicle at the desired yaw angle and the pitch attitude settings. As a result, overall vehicle has four controllers to perform the desired maneuvers.

Chapter IV "Simulation Technology" describes the complete simulation design and the tools used in the simulation. Simulink environment, S- function technologies, VRML and joystick usage for manual control is described in detail.

Chapter V describes the test cases for visualizing the dynamic behavior of the underwater vehicle under manual control inputs. Straight line flight, path following in a vertical plane, path following in a horizontal plane test cases are created and are tried to be kept along the desired path manually. Also the same tests are performed by using the depth and the heading controllers. Results of the path followed are recorded and are discussed in detail both for manually and automatic controlled cases.

Chapter VI is the conclusion chapter and includes the discussions related to the previous chapters. This chapter also presents the future work to complement the work initiated by this thesis.

CHAPTER 2

MATHEMATICAL MODELING OF UNDERWATER VEHICLE

2.1 Introduction

Mathematical modeling of underwater vehicles is a widely researched area and unclassified information is available through the Internet and from other source of written publications. The equations of motion for underwater vehicles are given in detail in reference [12], including the hydrodynamic stability derivatives of some of the underwater vehicles. The material presented in this chapter has been largely adapted from references [6] and [12].

In this chapter, the generalized six-degree of freedom (6 – DOF) equations of motion (EOM) for an underwater vehicle will be developed. The underlying assumptions are that: The vehicle behaves as a rigid body; the earth's rotation is negligible as far as acceleration components of the center of mass are concerned and the hydrodynamic coefficients or parameters are constant. The assumptions mentioned above eliminate the consideration of forces acting between individual elements of mass and eliminate the forces due to the Earth's motion.

The primary forces that act on the vehicle are of inertial, gravitational, hydrostatic and hydrodynamic origins. These primary forces are combined

to build the hydrodynamic behavior of the body.
The study of dynamics can be divided into two parts: kinematics, which treats only the geometrical aspects of the motion, and kinetics, which is the analysis of the forces causing the motion.

The chapter begins with an outline of the coordinate frames and the kinematics and dynamic relationships used in modeling a vehicle operating in free space. Basic hydrodynamics are presented. This discussion develops the foundation for the various force and moment expressions representing the vehicle's interaction with its fluid environment.

The control forces, resulting from propellers and thrusters and from control surfaces or fins that enable the vehicle to maneuver are then be detailed. With the hydrodynamic and control force and moment analysis complete full six degree of freedom equations of motion are formed.

2.2 Coordinate Systems, Positional Definitions and Kinematics

It is necessary to discuss the motion of an underwater vehicle in six degrees of freedom in order to determine its position and orientation in three dimensional space and time.

The first 3 of 6 independent coordinates (x, y, z) are to determine position and translational motion along X, Y, Z; the remaining 3 ($\emptyset,\theta,\psi$) are for orientation and rotational motion (See Figure 12). Conventionally for underwater vehicles the components mentioned above are defined as: surge, sway, heave, roll, pitch, and yaw respectively.

Obviously position/translational motion and orientation/rotational motion of a rigid body (a body in which the relative position of all its points is constant) can be described with respect to a reference position. For this purpose, some set of orthogonal coordinate axes are chosen and assumed to be rigidly connected to the arbitrary origin of the body to build up the reference frame.

Similarly, the forces and moments acting on the underwater vehicle need to be referenced to the same frame. In this thesis, standard notation from [12] and [6] is used to describe the 6 DOF quantities mentioned above and are summarized in Table 8.

Note that by convention for underwater vehicles, the positive *x*-direction is taken as forward, the positive *y*-direction is taken to the right, the positive *z*-direction is taken as down, and the right hand rule applies for angles.

DOF	Motions	Forces and Moments	Linear and Angular Velocities	Positions and Euler Angles
1	surge	X	u	x
2	sway	Y	v	y
3	heave	Z	w	z
4	roll	K	p	ϕ
5	pitch	M	q	θ
6	yaw	N	r	ψ

Table 8 Standard underwater vehicle notation. The notation is adopted from [12].

2.2.1 Reference Frames

As discussed earlier and outlined in Table 8 independent positions and angles are required and it is very important to describe clearly the reference frames in order to understand the kinematics equations of motion. There are two orthogonal reference frames; the first one is the earth fixed frame *XYZ* which is defined with respect to surface of the earth as illustrated in Figure 12. The earth fixed coordinate system to be used in this thesis is defined by the three orthogonal axes which are assumed to be stacked at an arbitrary point at the sea surface. These axes are aligned with directions North, East and Down. This produces a right-hand reference frame with unit vectors I , J , K . Ignoring the earth's rotation rate in comparison to the angular rates produced by the vehicle's motion, it can be said that the *XYZ* coordinate frame is an inertial reference frame in which Newton's Laws of

Motion will be valid.

A vehicle's position in this earth fixed frame will have the vector components:

$$r_{O'} = [XI + YJ + ZK] \qquad (1)$$

Secondly, a body fixed frame of reference $O'xyz$, with the origin O', and unit vectors i , j , k located on the vehicle centerline, moving and rotating with the vehicle is defined. The origin O' will be the point about which all vehicle body force will be computed. The vehicle's center of gravity (mass), *CG*, which is first moment centroid of vehicle’s mass, and center of buoyancy, *CB*, which is the first centroid of volumetric displacement of the fully submerged underwater vehicle do not generally lie at the origin of the body fixed frame.

It should be implied that all of the forces and moments acting on the underwater vehicle used in this thesis are assumed to be applied to the center of gravity location (normally assumed to be for a rigid body). The origin of the body fixed frame is exactly same as the center of buoyancy location. Therefore the center of buoyancy location will be the point about where all the hydrodynamic forces will be computed.

The positional vectors of the C_G and C_B relative to the origin of the body fixed frame are ρ_G and ρ_B, respectively, and can be represented in component form as $[x_G\, i + y_G\, j + z_G\, k]$ and $[x_B\, i + y_B\, j + z_B\, k]$.

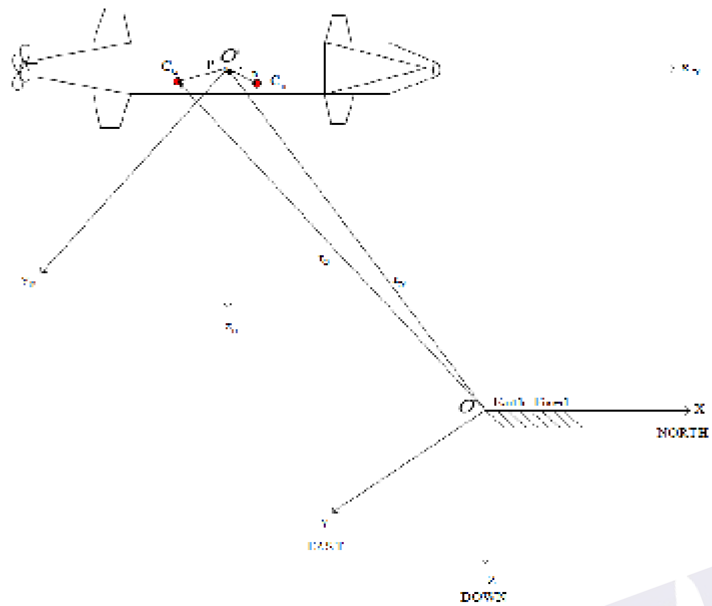

Figure 12 :Body-fixed and earth fixed reference frames

2.2.2 Euler Angles

When transforming from one Cartesian coordinate system to another, three successive rotations are performed. According to Euler's rotation theorem, an arbitrary rotation may be described by only three parameters. This means that to give an object a specific orientation it may be subjected to a sequence of three rotations described by the Euler angles. As a result, rotation matrix can be decomposed as a product of three elementary rotations.

Although the attitude of a vehicle can be described by several methods in earth fixed reference frame, the most common method is the Euler Angles method, which is used in this thesis. This method represents the spatial orientation of any frame of the space as a composition of rotations from a reference frame.

The earth fixed coordinate frame Euler angle orientation definitions of roll (ϕ), pitch (Θ) and yaw (ψ) implicitly require that these rotations be performed in order.

For the "roll, pitch, yaw" (XYZ) convention, a forward transformation is performed beginning with a vector quantity originally referenced in the body fixed reference frame. Then, through a sequence of three rotations it is transformed into a frame that is assumed to be attached to the surface of the sea.

To start the transformation, begin by defining an azimuth rotation ψ, as a positive rotation about the body *Z*-axis. Next define a subsequent rotation θ, (positive up) about the new *Y*-axis, followed by a positive rotation ϕ, about the new *X*-axis. The triple rotational transformation in terms of these three angles is then sufficient to describe the angular orientation of the vehicle.

The rotation and angular velocity conventions of body fixed coordinate system are given in and Figure 13.

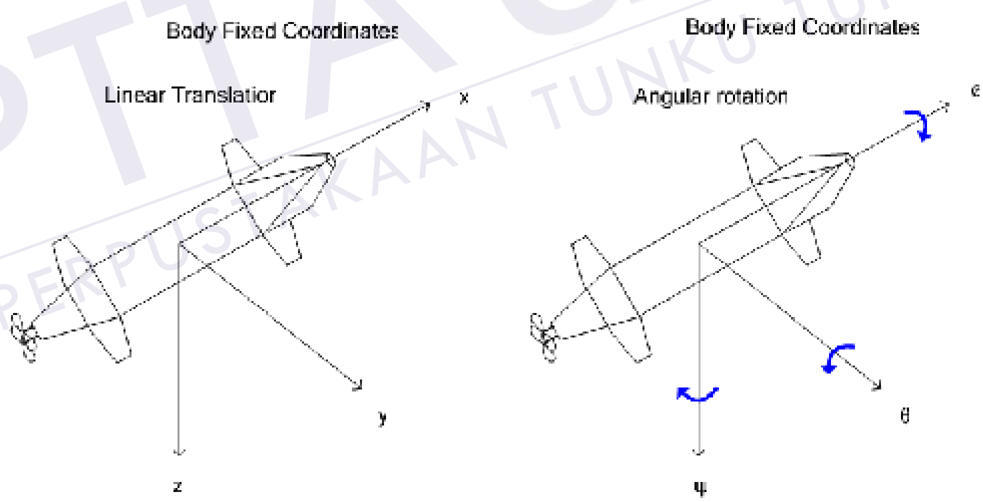

Figure 13: Body fixed coordinate system linear and angular velocity convention

As an example, any position vector, ro, in earth fixed reference frame given by ro = [Xo, Yo ,Zo], will have different coordinates in a rotated frame when a rotation by angle ϕ , is made about the earth fixed x0-axis.

If the new position is defined by r_1 = [X_1, Y_1 ,Z_1], it can be seen that the vector's coordinates in the new reference frame can be written with the coordinates in the old reference frame as:

$$Y_1 = Y_o \cos\phi + Z_o \sin\phi \qquad (2)$$

$$Z_1 = -Y_o \sin\phi + Z_o \cos\phi \qquad (3)$$

with $Z_1 = Z_o$. This relation can be expressed in matrix form by the rotation matrix operation,

$$r_1 = [R]^{-1}_{x_\circ,\phi}\, r_\circ \qquad (4)$$

where the rotation $[R]$ is an orthogonal matrix and the inverse of [R] equals its transpose.

$$[R]^T = [R]^{-1} \qquad (5)$$

Multiplication of this rotation matrix with any vector, r_o, will produce the components of the same vector in the rotated coordinate frame. Continuing with the series of rotations results in a combined total rotational transformation,

$$[R] = [R]_{z_\circ,\psi}\,[R]_{y_\circ,\theta}\,[R]_{x_\circ,\varphi} \qquad (6)$$

If Equation (6) is expanded it takes the form:

$$[R] = \begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi & \cos\phi \end{bmatrix} \qquad (7)$$

If matrix multiplications in Equation (7) are performed, finally [R] takes the form:

$$[R]=\begin{bmatrix} \cos\psi\cos\theta & \cos\psi\sin\theta\sin\phi-\sin\psi\cos\phi & \cos\psi\sin\theta\cos\phi+\sin\psi\sin\phi \\ \sin\psi\cos\theta & \sin\psi\sin\theta\sin\phi+\cos\psi\cos\phi & \sin\psi\sin\theta\cos\phi-\cos\psi\sin\phi \\ -\sin\theta & \cos\theta\sin\phi & \cos\theta\cos\phi \end{bmatrix} \tag{8}$$

It can be said that any position vector in a rotated reference frame may be expressed in terms of the coordinates of original reference frame given by the operation,

$$r_{ijk} = [R]^{-1} r_{IJK} \tag{9}$$

2.2.3 Kinematics

Kinematics defines the motion of an object without considering the mass and the external forces acting on the object during its motion. So, linear and angular velocities of the object are considered in kinematics. As mentioned in the previous section the linear and angular velocities are expressed in body fixed coordinate frame. The transformation of linear and angular velocities and prior to extending these transformations to accelerations from body fixed coordinate frame to earth fixed coordinate frame will be discussed in kinematics.

An earth fixed velocity vector can be written as,

$$r = \begin{bmatrix} \dot{X} \\ \dot{Y} \\ \dot{Z} \end{bmatrix} \tag{10}$$

These three translation rates can be obtained by selecting the linear components of the body fixed velocity vector and multiplying it by body to earth rotation matrix which is the rotational transformation matrix given in Equation (8):

$$\begin{bmatrix} \dot{X} \\ \dot{Y} \\ \dot{Z} \end{bmatrix} = [R] \begin{bmatrix} u \\ v \\ w \end{bmatrix} \tag{12}$$

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